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Magmatic evolution of the Jbel Boho alkaline complex in the Bou Azzer inlier (Anti-Atlas/Morocco) and its relation to REE mineralization

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The Jbel Boho complex (Anti-Atlas/Morocco) is an alkaline magmatic complex that was formed during the Precambrian-Cambrian transition, contemporaneous with the lower early Cambrian dolomite sequence. The complex consists of a volcanic sequence comprising basanites, trachyandesites, trachytes and rhyolites that is intruded by a syenitic pluton. Both the volcanic suite and the pluton are cut by later microsyenitic and rhyolitic dykes.

Although all Jbel Boho magmas were probably ultimately derived from the same, intraplate or plume-like source, new geochemical evidence supports the concept of a minimum three principal magma generations having formed the complex. Whereas all volcanic rocks (first generation) are LREE enriched and appear to be formed by fractional crystallization of a mantle-derived magma, resulting in strong negative Eu anomalies in the more evolved rocks associated with low Zr/Hf and Nb/Ta values, the younger syenitic pluton displays almost no negative Eu anomaly and very high Zr/Hf and Nb/Ta. The syenite is considered to be formed by a second generation of melt and likely formed through partial melting of underplated mafic rocks. The syenitic pluton consists of two types of syenitic rocks; olivine syenite and quartz syenite. The presence of quartz and a strong positive Pb anomaly in the quartz syenite contrasts strongly with the negative Pb anomaly in the olivine syenite and suggests the latter results from crustal contamination of the former. The late dyke swarm (third generation of melt) comprises microsyenitic and subalkaline rhyolitic compositions. The strong decrease of the alkali elements, Zr/Hf and Nb/Ta and the high SiO_2 contents in the rhyolitic dykes might be the result of mineral fractionation and addition of mineralizing fluids, allowing inter-element fractionation of even highly incompatible HFSE due to the presence of fluorine. The occurrence of fluorite in some volcanic rocks and the Ca-REE-F carbonate mineral synchysite in the dykes with very high LREE contents (Ce ~720 ppm found in one rhyolitic dyke) suggest the fluorine-rich nature of this system and the role played by addition of mineralizing fluids.

The REE mineralization expressed as synchysite-(Ce) is detected in a subalkaline rhyolitic dyke (with ΣLREE = 1750 ppm) associated with quartz, chlorite and occasionally with Fe-oxides. The synchysite mineralization is probably the result of REE transport by acidic hydrothermal fluids as chloride complex and their neutralization during fluid-rock interaction.

The major tectonic change from compressive to extensional regime in the late Neoproterozoic induced the emplacement of voluminous volcaniclastic series of the Ediacran Ouarzazate Group. The alkaline, within-plate nature of the Jbel Boho igneous complex implies that this extensional setting continued during the early Cambrian.

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1. Introduction

Rare earth element (REE) deposits are commonly associated with alkaline magmatic rocks. Economically relevant concentrations of REE in alkaline rocks most likely originate from both fractional crystallization of primary mantle melts and hydrothermal activities coupled with chloride-rich fluid immiscibility could lead to the formation of evolved rocks with high REE contents (Chakhmouradian and Zaitsev, 2012; Williams-Jones et al., 2012). Understanding the magmatic evolution of alkaline magmatic complexes may therefore provide basic information to allow better identification, during prospection, of those rocks of a complex that may contain elevated REE concentrations.

Deposits of economic importance are, for example, the syenite-hosted loparite deposits (loparite: $(Ca,La,Na,Ca,Sr)(Ti,Nb)O_3$) in the Khibiny and Lovozero complex in the Kola peninsula, Russia, (~30,000 tonnes of ore with 34 wt% rare earth oxides (REO)), the syenite-hosted eudialyte (eudialyte sensu stricto: $Na_{15}Ca_6Fe_3Zr_3Si[1](Si_{25}O_{73})(O,OH,H_2O)_3(Cl,OH)_2$) with the major part of the REE and Nb substituting Ca and Si[1]) in the Ilimaussaq alkaline complex in Greenland (~2 million tonnes with 1.5 wt% REO), and the Thor Lake syenite- and alkaline granite-hosted REE deposit in south-western Canada that contain about 65.6 million tonnes of ore with 2.53 wt% REO in monazite, allanite and REE-F-carbonate minerals (Orris and Grauch, 2002; Salvi and Williams-Jones, 2005).

Alkaline rocks are relatively rare on Earth (ca 1 vol% of all igneous rocks) and, although the majority of them occur in extensional geodynamic settings (e.g. in the East African rift system in Kenya; Baker (1987)), they can also form in other geodynamic settings, namely in compressive regimes like the Tamazert alkaline complex in the central High Atlas of Morocco (Bouabdellah et al., 2010) or even in the oceanic crust with relation to hotspot volcanism as exposed on Maio of the Cape Verde Islands (Le Bas, 1987).

Several alkaline provinces occur in Morocco: Oujda, Taourirt, Rekkam, Azrou and Oulmes in the Middle Atlas and the Tamazert complex in the High Atlas, which are of Tertiary ages, whereas the early Cambrian Jbel Boho, Saghro and Siroua complexes are situated in the Anti Atlas. Until recently only the Tamazert alkaline complex in the central High Atlas (Fig. 1) was known for REE mineralization e.g., monazite, parisite and synchysite (Bouabdellah et al., 2010; Mourtada, 1997; Woolley, 2001). Recently the Government's ONHYM (National Office for Hydrocarbon and Mines) published new exploration data with very promising Fe–Nb-REE concentrations in the region of Ouled Dlim south of Morocco (Moroccan Mauritanides) (Fig. 1). The Ouled Dlim complex consists of Fe-carbonatite including three intrusions emplaced along the western margin of the Archean Reguibat Shield. The results show generally very high REE contents up to 3 wt% (Mouttaqi et al., 2011; ONHYM, 2015, 2013; Qalbi et al., 2011; Zerdane et al., 2011). In addition, this study reports the occurrence of REE mineralization in the late rhyolitic dykes in the Jbel Boho alkaline complex. Leblanc (1971) already assumed a possible REE enrichment in the later alkaline intrusive dykes of Jbel Boho without testing this hypothesis by geochemical studies.

The Jbel Boho in the Bou Azzer inlier (Anti-Atlas) (Figs. 1 and 2) is a magmatic complex that was first described by Choubert (1952) and later by Leblanc (1981a, 1971). The alkaline nature of the Jbel Boho complex was first reported by Gasquet et al. (2005), Álvaro et al. (2006) and is confirmed by the present work.

The aim of the present study is to decipher in more detail the magmatic evolution of the Jbel Boho complex from primary to evolved rocks and the possible relationship of this evolution to the REE mineralization. We identify for the first time the occurrence of

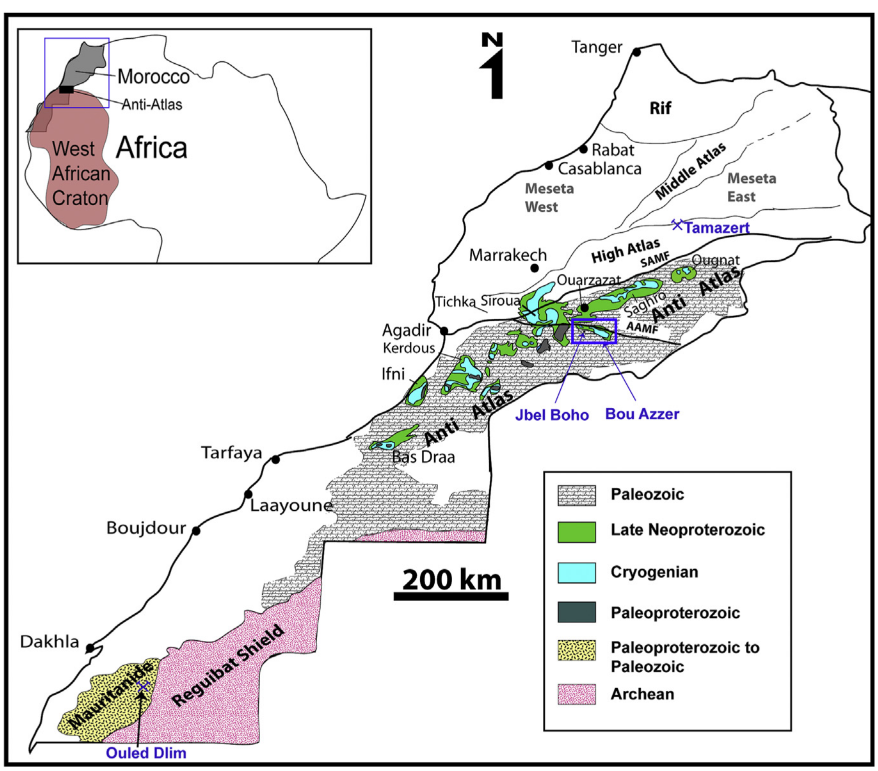

Fig. 1. Geological map of the Moroccan Anti-Atlas showing schematically the major geological domains of Morocco (Rif, Meseta East and West, as well as Middle and High Atlas) with the Jbel Boho complex within the Bou Azzer inlier in the Anti-Atlas. The approximate location of the Tamazert alkaline complex in the High Atlas, the location of the REE carbonatite complex of Ouled Dlim in the Mauritanide and the names of cities and other locations are added for orientation. Map modified after Gasquet et al. (2005) and Mouttaqi et al. (2011).